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Allen Pu, Demetri Psaltis, "High-density storage in holographic 3D disks," Proc. SPIE 2604, High-Density Data Recording and Retrieval Technologies, (15 January 1996); doi: 10.1117/12.230061

Event: Photonics East '95, 1995, Philadelphia, PA, United States

Invited Paper

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ABSTRACT

We have achieved a surface density of 10 bits/μm^2 (6.5 Gbits/in^2) with an experimental holographic storage setup, using DuPont's 100 μm thick photopolymer as the recording medium. Its performance characteristics in terms of access rate and signal-to-noise-ratio will be described. Furthermore, a simple holographic 3D disk system with high surface density (10 bits/μm^2 using a 100 μm thick recording material) and an architecture similar to compact disks will be shown.

Keywords : holography, 3D disks, photopolymer, high density.

1. INTRODUCTION

Holographic data storage offers several advantages when compared to conventional storage devices. The data to be stored and retrieved is organized as a two dimensional page, consisting of a large number pixels (bits). Therefore, the read-out rate can be very high. For example, accessing a page of data consisting of 1000×1000 pixels within 1 ms would give an access rate of 1 gigabit per second. Furthermore, holographic data storage allows for many pages of data to be stored at the same location with little cross-talk by using multiplexing techniques such as angle[1,2], wavelength[3,4], phase-code[5,6], fractal[7,8], peristrophic[9], and shift[10]. The surface density achievable with holography is simply the density per page times the number of holograms multiplexed. For thick recording materials (> 1 mm), the surface density can easily approach 100 bits/μm^2.

Holographic storage was first demonstrated more than 20 years ago[11,12] and has since laid mostly dormant due to the lack of necessary optical devices and the need for such high density device. The situation has now changed completely. During the last decade, opto-electronic technology has provided us with a rich variety of compact, inexpensive, and high performance semiconductor laser diodes, liquid crystal spatial light modulators (SLM), and CCD detector arrays. Furthermore, the recent dramatic advances in electronic computers have led to ever increasing demand for inexpensive mass storage devices. Optical storage devices have already emerged as the preferred storage technology for removable ROM media and will continue to increase its market share with the introduction of newer technologies[13,14]. However, it appears that the density of conventional optical storage devices (e.g. CD-ROM) will not be able to increase rapidly enough to satisfy the requirements of some applications (large data base archive, video-on-demand, etc.). Therefore, a 3-D memory technology, such as holographic storage with its high access rate and high density is now appealing.

2. HOLOGRAPHIC 3D DISK

The recent resurgence of interest in holographic data storage is mostly due to the large scale demonstrations of holographic memories in $LiNbO_3$[15,16] and photopolymers[17] we have been able to construct using modern components. One architecture of interest is the holographic 3-D disk[18,19]. The schematic diagram of a holographic 3-D disk is shown in Figure 1. It consists of a holographic disk (a thick recording material in the shape of a disk mounted on a suitable substrate), a mechanical drive that spins the disk, and a read/write head. The optical head consists of an SLM, relay optics, a mechanism for multiplexing holograms, and a CCD for hologram read-out. The entire head can translate in the radial direction to access different tracks on the disk. Holograms stored at a particular location can be retrieved by illuminating the location with a reference beam at the proper angle or wavelength. The holographic medium can be either a photorefractive crystal, such as $LiNbO_3$, or a photopolymer film, such as the HRF-150 material that is available from DuPont[20]. Photorefractives are re-programmable, optically erasable and can be made to large thickness with good optical quality. Photopolymers on the other hand are inexpensive, easy to laminate to large surfaces and offer non-volatile storage. In the remainder of the paper we will describe a specific design of an optical disk system based on the DuPont photopolymer.

3. HIGH DENSITY EXPERIMENT

The surface density of conventional optical memories (~ 1 bit/μm^2) is determined primarily by the size of the illuminating spot. For holography, the surface density is determined by the density per page of hologram and the number of holograms that can be multiplexed. To a first approximation, the density of a holographic disk is given by :

$$D_{3D} = M \times D_{2D} \tag{1}$$

where D_{3D} and D_{2D} are the surface densities achievable with a 3-D and 2-D medium, respectively and M is the maximum number of holograms that can be multiplexed at each location. The density predicted by Equation (1) is a theoretical upper limit that can be difficult to achieve in practice. For example, Equation (1) holds only if the resolution of the conventional CD lens and the relay lenses in the signal arm of the system in Figure 1 are the same. This is possible but difficult since the 3-D memory must maintain the same resolution over a large field whereas the CD only needs to produce a single spot at the optical axis of the lens. The recording medium's dynamic range can also limit the storage density since the diffraction efficiency falls off as $1/M^2$. Finally, some noise sources such as cross-talk increase as M gets larger. In a practical system, the storage density is maximized by optimizing the optical design while monitoring the signal-to-noise ratio of the reconstructed holograms.

We have experimentally demonstrated storage density of 10 bits/μm^2 in a 100 μm thick DuPont photopolymer film. A diagram of the experimental setup is shown in Figure 2. A glass mask plate of a random binary bit pattern was used as the input SLM. The center-to-center spacing of the pixels was 45 microns and the fill factor was 100%. Nikon F/# 1.4, 4 cm aperture camera lenses were used for imaging. A total of 590,000 pixels fit in the apertures of the two Nikon lenses and a sharp image of the entire field was obtained at the CCD plane. The holograms were recorded with a plane wave reference beam approximately .5 mm past the Fourier transform plane. At that position, the diameter of the signal beam was 1.5 mm and its spatial uniformity was much better than at the exact Fourier plane. For the 100 micron thick recording medium, the angular separation to the first null of the Bragg selectivity was approximately .7 degree in our setup. In order to minimize cross-talk between holograms, we angularly multiplexed 8 holograms, each separated by 2.5 degrees. Angle multiplexing was achieved by rotating the film instead of changing the reference beam angle. To increase the density further, we combined angle multiplexing with peristrophic multiplexing. Specifically, sets of 8 angularly multiplexed holograms were recorded at 4 different peristrophic positions. Each peristrophic position corresponds to a different rotational angle of the recording medium around the axis perpendicular to the surface of the medium. Using this method, we stored a total of 32 holograms at a single location. One of the 32 reconstructions is shown in Figure 3. The surface density of each hologram is 590,000 bits / ($\pi \times .75 \times .75$ mm^2) which is equal to .334 bits per micron squared. Since 32 holograms are superimposed in the same region, the overall surface density is $32 \times .334 = 10.68$ bits/μm^2. We can improve the density of the current system further by using lower F/# lenses (increase D_{2D}), reducing the angular separation between holograms, and increase the range of angles over which holograms can be recorded (increase M). The density can of course be increased by a large factor if a thicker recording medium is used.

The rate at which data is recorded on a holographic disk is given by the number of pixels per page divided by the time required to record one hologram. For our setup, a recording rate of 0.7 Mbits/s was achieved by recording 590,000 pixel holograms in an average recording time of 840 ms per hologram. The total incident intensity was 2 mW/cm^2 and the diffraction efficiency per hologram was 0.35%. From our experimental observations with plane wave holograms, the recording time for achieving the same diffraction efficiency is approximately inversely proportional to the incident intensity for intensities greater than 2 mW/cm^2. Therefore, if the total incident intensity is increased from 2 mW/cm^2 to 128 mW/cm^2, then the recording time per hologram drops to 12 ms and the recording rate could be as high as 50 Mbits/s.

A read-out rate of .13 Mbits/s was demonstrated in the same experimental setup. Since the reconstructed hologram was much larger then the CCD detector array used, windows of 65 $\times$ 65 pixels from the reconstructed hologram were read-out at video rate with a CCD camera. In an optimized system with full parallelism, a large CCD detector array would be used to read out the entire 590,000 pixels in a minimum frame-transfer-rate of 1000 frames/s to achieve a read-out rate greater than 500 Mbits/s.

One of the most important measures of a storage device is its bit-error-rate, or equivalently, the signal-to-noise ratio. Holographic 3-D disks are subjected to many sources of noise such as cross-talk between holograms, lens aberrations, recording material scattering, multiple reflections, noise from the SLM, laser noise, recording material surface imperfections, dust, and the index modulation from previous holograms. There is also the shrinkage effect that is inherent in the photopolymer material, which makes it difficult to Bragg match the entire hologram for read-out. We have studied in detail many of these sources of noise and we minimized them with a proper setup. For our system, we sampled 9 different 65 $\times$ 65 pixel windows from the stored holograms and no errors were detected. The combined histogram from the 9 different sampled windows is shown in Figure 4. An estimated bit-error-rate of 10^{-4} was obtained by fitting a first-order χ^2 distribution to the histogram. This is the raw bit-error-rate since no error correction codes were used.

4. SHIFT MULTIPLEXED HOLOGRAPHIC 3D DISK

The high density experiment discussed in the previous section involves recording holograms at only a single location. With the holographic 3D disk, we would like to spatially multiplex (record at many locations) to increase the capacity of the disk. However, the setup used in the high density experiment does not extend well to spatial multiplexing (tilting of the disk would be required to angle multiplex). It is possible to redesign the setup so that both angle and peristrophic multiplexing can be accomplished without any movements on the part of the recording material (as shown in Figure 1). But, this means that a complicated reference beam delivery system capable of scanning the angle and rotating around the signal beam would have to be constructed. Instead, we would like to propose a completely different multiplexing method call "shift" multiplexing[10]. With shift multiplexing, a spherical reference beam is used instead of a plane wave beam and the multiplexing mechanism is a small shift of the recording material. After a hologram is recorded with a spherical reference beam on axis, shifting the recording material in a direction that is perpendicular to the reference beam and in the plane formed by the signal and the reference causes the hologram to disappear. The diffraction efficiency of the stored hologram as a function of shift distance is a sinc function and the amount of shift required to reach the first null is given by the following expression:

$$\delta = \frac{\lambda Z_o}{L \tan \theta_s} + \frac{\lambda}{2(NA)} \qquad (2)$$

where λ is the wavelength, Z_o is the distance between the recording material and the focal point of the spherical reference beam, L is the thickness of the recording material, θ_s is the angle between the reference and signal beam, and NA is the numerical aperture of the reference beam lens (to generate the spherical reference beam). For example, using the same numbers from the high density setup (L = 100 μm, λ = 532 nm and picking appropriate Z_o, θ_s and NA) a shift of only 24 μm is required to reach the first null. The actual width of the hologram from the high density experiment is 1.5 mm. This means that up to 31 holograms can be multiplexed at the second null of the sinc function within the 1.5 mm hologram width (1.5 mm/ 48 μm $\simeq$ 31 holograms). The surface density in this case will be 31 holograms $\times$ .334 bits/μm^2 density per page, or 10.33 bits/μm^2. Therefore, the density achievable with shift multiplexing is comparable to the high density experiment, except now, the reference beam remains stationary and the multiplexing of holograms is achieved by a small shift of the recording material.

This elegant multiplexing method gives rise to the simple holographic 3D disk design shown in Figure 5. The system consists of two major components: the read/write head and the holographic 3-D disk. The read/write head is mounted on a mechanical slide so that the spherical reference beam can access different tracks on the disk. The holographic 3D disk spins so that different stored holograms get reconstructed by the spherical reference beam. Notice that there are no moving parts inside the read/write head and only about ten components are required. Furthermore, holograms are read out in a continuous fashion by the spinning motion of the disk. The holographic 3D disk setup shown in Figure 5 offers both the simple CD-like architecture and high speed page access.

5. ACKNOWLEDGMENTS

We gratefully acknowledge the Air Force Office of Scientific Research for sponsoring this research project.

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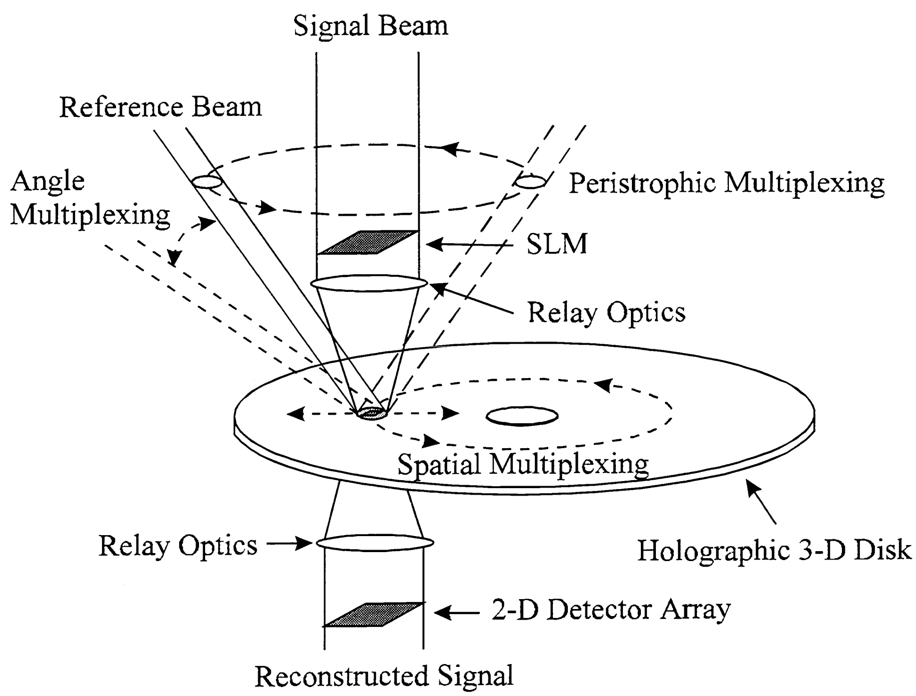

Figure 1: Holographic 3-D disk setup.

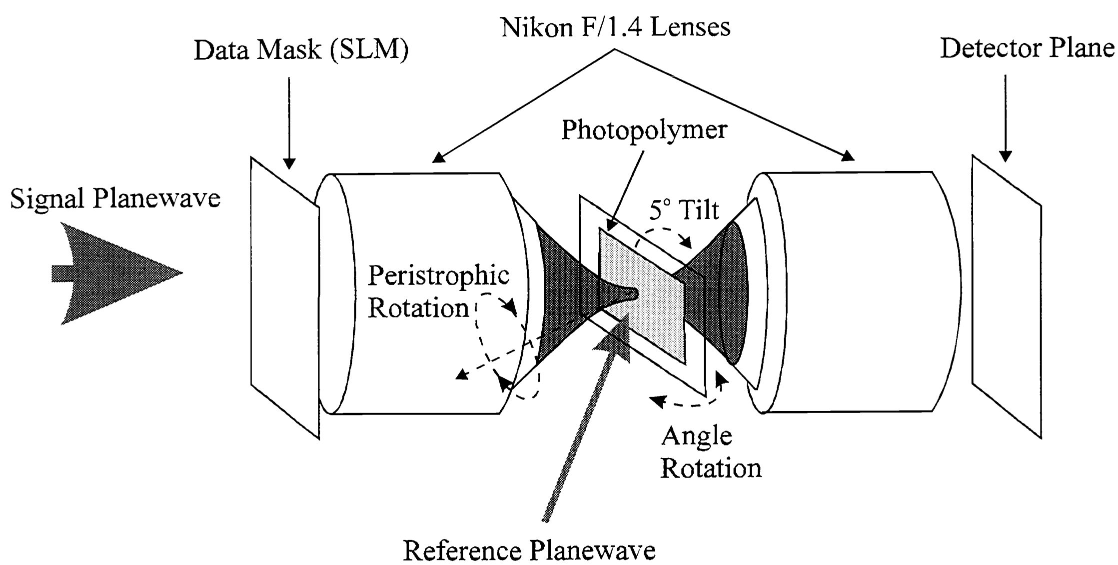

Figure 2: High density holographic storage setup.

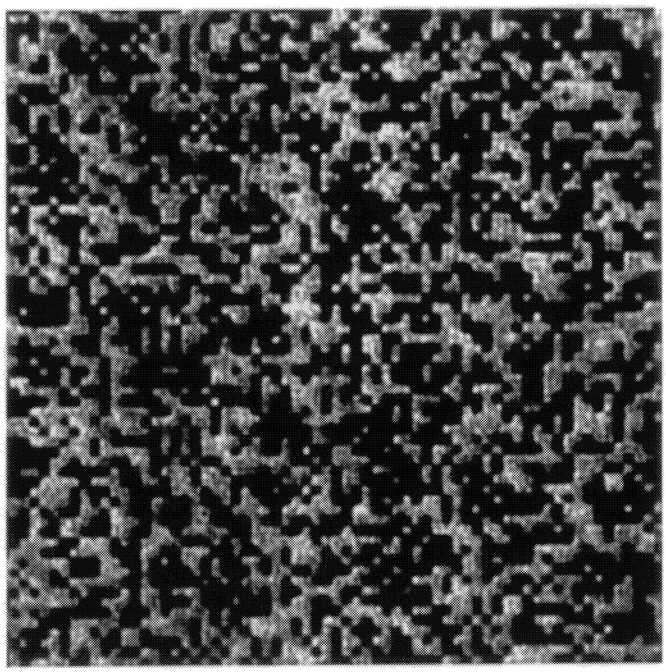

Figure 3: A window from the reconstruction of one of the 32 holograms stored using the setup shown in Figure 2.

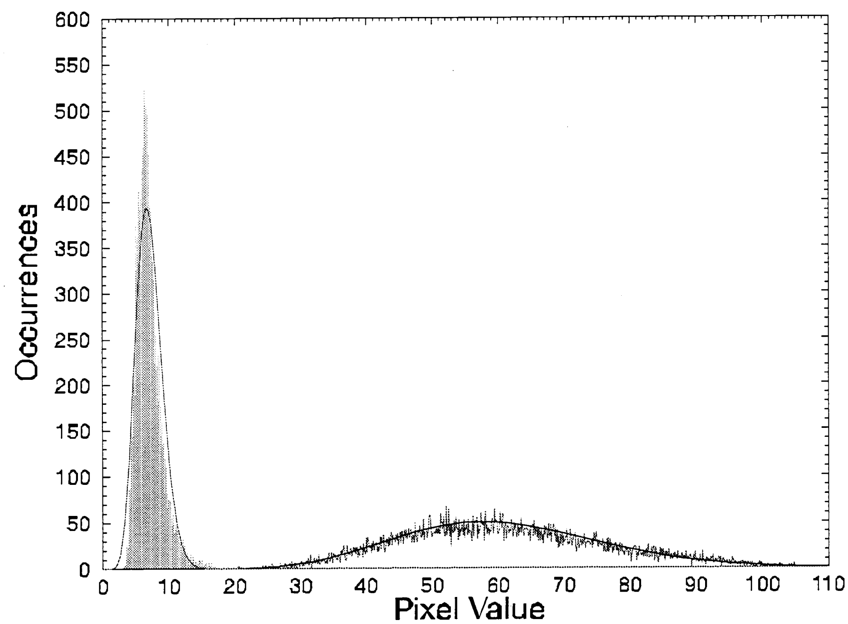

Figure 4: Combined histogram of the 9 sampled reconstructions.

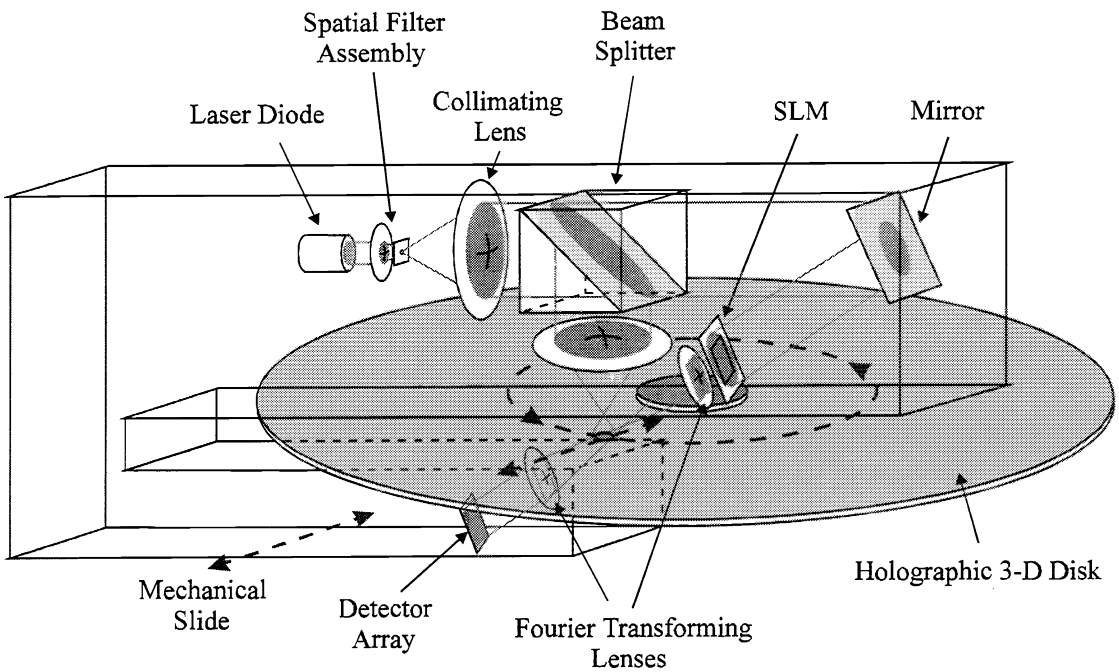

Figure 5: Holographic 3D disk using shift-multiplexing.